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MINING EXPLOSIONS IN THE KHIBINY MASSIF (KOLA PENINSULA OF RUSSIA) RECORDED AT THE APATITY THREE-COMPONENT STATION

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This technical report has been reviewed and is approved for publication.

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This report offers a description of the three-component seismic station that was installed in Apatity on the Kola Peninsula of Russia in June of 1991. Data from this station are useful for studying mining explosions in the nearby Khibiny Massif. Colleagues at the Kola Regional Seismological Center in Apatity have provided us with detailed information on 200 mining explosions undertaken during June 1991-September 1992, and we have compiled a data base comprising data from 61 of these explosions. The data are used to estimate the noise level at the Apatity station, and also for estimation of P-wave arrival azimuths, using a broad band slowness analysis technique. Values for the true azimuths are available from information presented in this report, and the azimuth residuals are found to have a median value of -7.06 degrees. A small-aperture array was installed close to Apatity in the fall of 1992, and some perspectives for the future use of data from Apatity are discussed.

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Preface

Under contract No. F49620-C-89-0038, NTNF/NORSAR is conducting research within a wide range of subjects relevant to seismic monitoring. The emphasis of the research program is on developing and assessing methods for processing of data recorded by networks of small-aperture arrays and 3-component stations, for events both at regional and teleseismic distances. In addition, more general seismological research topics are addressed.

Each quarterly technical report under this contract presents one or several separate investigations addressing specific problems within the scope of the statement of work. Summaries of the research efforts within the program as a whole are given in annual technical reports.

This Scientific Report No. 14 presents a manuscript entitled "Mining Explosions in the Khibiny Massif (Kola Peninsual of Russia) Recorded at the Apatity Three-component Station", by S. Mykkeltveit.

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1. Introduction

As part of an agreement on scientific cooperation between NORSAR and the Kola Science Centre of the Russian Academy of Sciences, a three-component seismic station was installed in Apatity on the Kola Peninsula of Russia in June of 1991. This station provided for an extension of the regional network of small-aperture arrays and single, three-component stations in northern Europe contributing data to the NORSAR Data Processing Center. The configuration of this network as it was operated from June 1991 through September 1992 is shown in Fig. 1.

Recordings from the Apatity three-component station are useful for studying mining explosions in the nearby Khibiny Massif (distances 17 to 33 km from the station). These events are also well recorded on the ARCESS array (distance 400 km), and many of them also on the more distant FINESA and NORESS arrays. It is thus of significance to have available near-field recordings, as offered by the Apatity data.

This report presents general information on the mining activity in the Khibiny Massif, as well as results from analysis of recordings of such mining explosions made at the Apatity three-component station. For many of the Khibiny Massif mining explosions undertaken during June 1991 - September 1992, we have obtained information on their location and total charge sizes. We have compiled a data base of altogether 61 such Apatity three-component station recordings The data are used for computation of the noise level at the station, and in addition, broad band slowness analysis is applied to estimate P-wave arrival azimuths, and these azimuth estimates are compared to the true azimuths.

2. The Apatity three-component station

A high-quality three-component station was installed in Apatity, on the Kola Peninsula of Russia in mid-June 1991, as part of a cooperative agreement between NORSAR and the Kola Science Centre of the Russian Academy of Sciences. The station is operated under this agreement by the Kola Regional Seismological Centre of the Kola Science Centre.

The three-component station installed in Apatity initially comprised S-13 seismometers, a Nanometrics RD3 digitizing/synchronization/multiplexing unit, an Omega clock and a PC-based system for data acquisition, analysis and archiving. The amplitude response of the system is shown in Fig. 2. The PC system had a 25 MHz 386 processor, 4 Mbyte RAM, a 300 Mbyte ESDI disk, and a cartridge tape drive. The seismometers were installed in the basement of the building of the Kola Regional Seismological Centre of the Kola Science Centre, in the town of Apatity. The S-13 seismometers were placed on the same pad as the seismometers of the analog APA station (established in 1956). Until November 1991, data were recorded continuously on magnetic disk in Apatity. During November 1991 - June 1992, the system in Apatity was operated in trigger mode. All data recorded in Apatity during June 1991 - June 1992 were copied to cartridge tapes and sent to NORSAR. An archive of data from this period is thus maintained both at Apatity and at NORSAR.

Significant changes were made to this system in June 1992, when a satellite link, based on Norwegian Telecom's NORSAT B system, was installed between NORSAR and the Kola Regional Seismological Centre in Apatity. A computer-to-computer Ethernet connection was established over this link. This enables NORSAR to retrieve continuous data from the

system in Apatity. At the same time, several Sun workstations for data analysis were installed in Apatity, and a NORAC array controller (Paulsen, 1992) replaced the PC system with regard to the data acquisition function. The configuration was otherwise unchanged, and the system response was not affected by these changes. From June 1992, continuous data from the Apatity station are stored on Exabyte cassettes at NORSAR. In late September 1992, the systems in Apatity were again changed, in conjunction with the installation of a small-aperture array outside Apatity. The data analysis reported on in this contribution is, however, limited to three-component short-period data recorded during June 1991 - September 1992.

The location of the Apatity three-component station was measured by a Magellan GPS NAV 5000 unit in November 1992, and the geographical coordinates are 67.5686°N, 33.4050°E. The elevation is 175 m.

3. Mining activity in the Khibiny Massif

Fig. 3 shows the location of six apatite mines in the tectonically unstable Khibiny Massif close to Apatity. The location of the three-component station at Apatity is denoted by APA. Mining activity in terms of rock removal and its relation to induced seismicity is described by Kremenetskaya (1991). More than $2 \cdot 10^9$ tons of rock mass has been removed from these mines over an area of approximately 10 km^2. Fig. 3 also shows 25 induced earthquakes that occurred in this area during the years 1948-1989.

Mine locations

The location of the mines as well as true azimuth and distance from the Apatity three-component station are given in Table 1. The information presented in this table is derived from various sources, as described in the following:

Mine I: This is the so-called Kirovsk mine. This mine consists of both an underground mine and an open-pit mine. The underground mining currently takes places at two different levels. The position of the underground mine at Mine I given in Table 1 corresponds to the position of a blast that occurred on 7 November 1992 at 06.31 GMT (V.M. Trjapitsin, personal communication). The position of the 7 November shot was pointed out on a map of the mine, and the corresponding geographical position was calculated from reference points on this map, the location of which were derived from GPS-based measurements made during a visit to Apatity in November 1992. We take this location to represent the position of the underground mine at Mine I, as it appears that the 7 November blast was relatively centrally located in this mine. The lateral extent of the underground mine is approximately 2 km x 1 km, and the associated azimuths relative to the Apatity three-component station are between 47° and 53° for shots within this underground mine.

The position given in Table 1 for the open-pit mine at Mine I is also based on GPS measurements made in November 1992. This mine is approximately circular in shape, with a diameter at the rim of about 700 meters. The location given in Table 1 for this mine is the location at the center bottom of the mine, based on GPS measurements made at the rim. For blasts within this crater, the true azimuth from the Apatity three-component station is in the interval 52° to 54°.

Mine II: This is an underground mine slightly to the southeast of Mine I. This mine is named after the mountain Yukspor on top of the mine. The location of this mine as given in Table 1 is derived from information provided to us (mostly in the form of maps) by Elena O. Kremenetskaya and Victor M. Trjapitsin of the Kola Regional Seismological Centre, and we have not yet made any on-site GPS measurements as was done for Mine I. This is also the situation with respect to Mines III-VI described below. The positions given for these mines are based on interpretation of the various maps provided to us by the staff of the Regional Seismology Centre.

Mine III: This mine is composed of both an underground mine and an open-pit mine. The name of the mine is Rasvumchorr.

Mine IV: This is an open-pit mine. According to the information we receive regularly (see below) on these mining explosions, this is the most active mine after Mine I. Also, the majority of the larger blasts (> 300 tons) occur in this mine. Its name is Centralny.

Mine V: This is an open-pit mine. Mines V and VI have the same administration, and the overall name of these mines is Koashva. Mine V is referred to as the Nostochny mine.

Mine VI: This is also an open-pit mine. There are relatively few explosions in this mine. Mine VI is named Njorkpahk.

Information on individual mining shots

The Kola Regional Seismology Centre has since the beginning of 1991 submitted to NORSAR on a regular basis information on mining blasts in the Khibiny Massif Mines I-VI described above. The information provided contains an assignment of the relevant mine (I-VI), P (and normally also S) arrival times at the analog APA station (co-located with the digital three-component station described in this report), the amplitude and period of the signal at this station, and the total charge size in tons. The information provided during the time of operation of the digital three-component station in Apatity is given in Table 2, which contains information about altogether 200 mining explosions in the Khibiny Massif.

Further general information on the mining explosions

As described above, Mines I and III both accommodate an underground and an open-pit mine. We have been informed (Victor M. Trjapitsin, personal communication) that in Mine I all small (of the order of 10 tons) explosions occur in the open-pit mine, whereas the larger explosions occur underground. We have interpreted this to mean that all explosions in Mine I in Table 2 with charge size equal to or less than 15 tons, occurred in the open-pit mine of Mine I, whereas all explosions in Mine I with charge size exceeding 15 tons (the smallest of these has a size of 40 tons) occurred underground. The distribution of explosions in Mine III (underground versus open-pit) is not yet known to us.-

The explosive used in the blasting is ammonium. Most of the drill holes for the explosives have a diameter of 105 mm, and are typically 25-30 m in length. The explosive mass per meter drillhole is 9 kg. Occasionally, a drill hole diameter of 125 mm is used, and the corresponding explosive mass per meter drillhole is then 12.5 kg. The blasting technique is ripple-fire, with 25 ms as a typical delay time between individual shots in the blasting

sequence. Typical total duration for the smaller explosions is 100 ms, whereas the larger explosions have typical total durations of 300-400 ms.

4. Data base of Apatity three-component recordings

Starting from the list given in Table 2, we have selected 61 explosions in the mines in the Khibiny Massif for further study. For these events, we have retrieved the digital records at the Apatity three-component station and compiled a data base comprising these records and the associated parametric information (arrival times of P and S, mine identifier, charge size). The length of each record is 180 seconds, and the start time is 60 seconds prior to the P arrival time. The arrival times are read from these records and do not always fully match those given for the corresponding events in Table 2, which are based on readings by the staff of the Kola Regional Seismological Centre made on their co-located analog station.

The events in the data base are given in Table 3. We made the selection such that all mines are represented, and such that the available range of charge sizes is adequately sampled. As seen from Table 3, no events during the time interval early November 1991 through mid-June 1992 were included in this data base. The reason here is that data were recorded during this time interval with the Nanometrics recording system in trigger mode (see paragraph 2 above). We have not yet developed all necessary software to utilize these data; however, waveforms are available on tape and can be utilized in the future with some extra programming effort.

For a few (6) of the events in Table 3, we were not able to retrieve from the cartridge tapes the waveform data for all three components. The parameter "Navail" in Table 3 indicates how many components are available (A value of 1 (3 cases) indicates that only the vertical component is available; a value of 2 (3 cases) indicates that the vertical and north-south components are available).

The data base comprises 23 shots from Mine I (10 underground, large ones and 13 from the open-pit mine), 1 from Mine II, 6 from Mine III, 18 from Mine IV, 12 from mine V and 1 from Mine VI.

An example of the data in the data base is given in Fig. 4, which shows the Apatity three-component station data for the event denoted "$A_{pa}7$" in Table 3. 30 seconds of data are plotted in Fig. 4. The upper three traces are the unfiltered data for the three components, then follow the same data filtered in the 0.5-2.0 Hz band, and the bottom three traces show the data filtered in the 7-16 Hz band. Three distinct phases can be seen: Pg, Sg and Rg (Rg in particular in the 0.5-2.0 Hz band).

5. Data analysis

The data base described in the previous paragraph and comprising 61 records from mining explosions in the Khibiny Massif has been subjected to analysis as described in the following. The main use of the data is the broad-band slowness estimation of P-waves, but first we present results on the noise level at the Apatity three-component station.

Noise level at the Apatity three-component station

Fig. 5 shows the average noise spectrum for the Apatity three-component station, and curves corresponding to plus/mins one standard deviation. The spectra are based on 61 noise samples each of length 30 seconds, and correspond to noise on the vertical channel prior to the P-wave signals for the events listed in Table 3. The noise spectra have been estimated using the indirect covariance method. We first estimated the correlation function by splitting the data record in to several windows, calculating a sample correlation function for each window, then averaging the sample correlation functions. Because the earth noise has such a large dynamic range, we prewhitened it prior to estimating the correlation function with a low-order prediction-error filter. The spectrum was estimated by windowing the correlation function with a 3-second Hamming window, then computing the Fourier Transform. The spectral estimate obtained this way was compensated for the effects of prewhitening.

As seen from Table 3, the noise samples used to produce Fig. 5 are with two exceptions only taken between 03 and 16 hours GMT. The local time is 3 hours (during daylight saving time, 4 hours) ahead of GMT, so this noise level largely represents day-time noise. The trend of the noise curve strongly indicates cultural origin for the noise above about 2 Hz. It must be kept in mind that the station is located within the town of Apatity, which together with the nearby town of Kirovsk has about 100,000 inhabitants. The distinct peak at 4 Hz indicates a specific and localized source. The peak at 4 Hz can be observed on all individual spectra, and for some of the noise samples the corresponding 4 Hz wave can be seen in the seismograms (Fig. 4 provides an example of this). The average spectrum of Fig. 5 also exhibits a peak at 2.5 Hz, and this peak can be observed on the large majority of the individual spectra, but it is not quite as consistent as the 4 Hz peak.

As mentioned previously, a small-aperture array was installed near Apatity in the fall of 1992. The new array comprises nine seismometer sites and is located approximately 17 km to the west of the three-component station described in this report, and thus well outside the town of Apatity. Preliminary analysis of the data from the new array shows a substantially lower noise level above 2 Hz than at the three-component station. At 10 Hz, for example, the power density at the array site is around 10^{-4} nm^2/Hz as opposed to 10^{-1} nm^2/Hz at the three-component station. In comparison, the power density at 10 Hz in Fyen's (1990) NORESS noise model is about $10^{-5} nm^2/Hz$. Spectra taken at the new array also exhibit a distinct peak at 4 Hz, although the corresponding power density is much lower than in the town of Apatity. This indicates that the source of the 4 Hz peak is located close to the three-component station, and it may be possible to pinpoint it by combined analysis of the array and the three-component data. The new array is described in Mykkeltveit et al. (1992), and some preliminary results from analysis of data recorded at the array are given in Ringdal and Fyen (1992).

Broad-band slowness analysis of P-waves from Khibiny Massif mining explosions

The P-waves for the mining explosions given in Table 3 were analyzed to derive the apparent arrival azimuth, using the broad-band slowness estimation technique of Kværna and Doornbos (1986). Altogether 55 P-wave records, corresponding to those events in Table 3 for which all three components are available, were used in the analysis. The calculations were made for four different frequency bands, with variable window lengths. The time windows used were 1.0 s for the 8-16 Hz band, 1.5 s for the 5-10 Hz and 3-5 Hz

bands, and 2.0 s for the 1-3 Hz band. The start time of the windows was 0.3 s prior to the P arrival time given in Table 3.

The position of the six mines and the true azimuth from the Apatity three-component station to each of the mines are given in Table 1. The values represent center points in the mines, and due to their lateral extent, true azimuths for individual shots in the various mines may deviate by as much as ± 3 degrees from the values given in this table.

For each of the four filter bands, the signal-to-noise ratio (SNR) was computed from the vertical component for all 55 P-wave signals. The SNR was computed as the maximum value of the STA/LTA ratio, where the STA was estimated over a 0.5 s long window sliding over the first two seconds of the P-wave signal, and the LTA was computed over a fixed 30 s long noise window ahead of the P-wave arrival. The azimuth residuals (estimated azimuth minus true azimuth) as resulting from the slowness analysis, are plotted versus SNR for all 55 events and all four filter bands in Fig. 6. The median value of the residuals is -7.06 degrees. As can be seen from Fig. 6, the residuals are largely independent of SNR for SNR values above about 3. Figs. 7-10 show the true versus estimated azimuths for each of the four filter bands, for values of SNR exceeding 3. The pattern of residuals is similar for the different frequency bands (median values are -7.2 degrees for 1-3 Hz, -11.2 degrees for 3-5 Hz, -4.6 degrees for 5-10 Hz, and -9.6 degrees for 8-16 Hz). The overall picture is then that the P-waves from the Khibiny mining shots appear to arrive with azimuths slightly rotated towards the north relative to the true azimuths. The median residual value of -7 degrees over all shots and azimuths is, however, not much different from what has been found earlier in similar analyses of three-component data, and we take this value to indicate that the Apatity station performs well from a technical point of view.

6. Discussion, conclusions and future perspectives

The Khibiny Massif on the Kola Peninsula of Russia is one of the most active mining areas in Fennoscandia, and the recording and analysis of explosions from this source region is a topic of high interest to the assessment of the capabilities of the high-frequency array network in northern Europe. In this context, the Khibiny Massif is an important source region not only because of the high number of explosions, but also because of the distribution of explosions between a number of nearby mines, and also because of the seismicity in the region, induced by the mining activity (Kremenetskaya and Trjapitsin, 1992). We have in this report presented our current knowledge on location of mines in the Khibiny Massif, and some preliminary information on firing practice, etc., is included. The report also contains information on total charge size for 200 individual explosions conducted during June 1991 through September 1992. All the information is obtained through our close cooperation with the staff of the Kola Regional Seismological Centre in Apatity. We will continue this cooperation, which we expect will result in further independent information on the Khibiny Massif mining activity.

This report offers a description of a three-component short-period station that was installed in Apatity in June 1991, providing near-field records from the Khibiny Massif mining explosions. We have compiled a data base of 61 waveforms from such explosions recorded at this station during June 1991 - September 1992. We have used this data base to establish the ambient noise level at the Apatity three-component station, and also in a study to estimate the arrival azimuth of P-waves from the mining explosions. These esti-

mates have been compared to the true values, derived from the independent information provided to us. This comparison has given a median azimuth residual of - 7.06 degrees for all shots and frequency bands used in the analysis. The analysis also showed that the azimuth residual is largely independent of SNR, for SNR values exceeding a value of about 3.

The data base that has been compiled can be used for further studies of the Khibiny Massif mining explosions. It would be of interest, e.g., to study the P-wave spectra in relation to mine location, shot locations underground versus in open-pit mines, and total charge size. The data base compiled will be available to those who plan to perform such or other investigations.

A small-aperture array comprising nine seismometer sites and including a high-frequency three-component station was installed about 17 km to the west of the town of Apatity in October 1992. At the same time, the short-period system located in Apatity and described in this report was replaced by a broad band system. This increase in seismic instrumentation close to the Khibiny Massif should lead to a greatly enhanced possibility of studying the mining explosions in detail.

The data from the systems installed in Apatity in the fall of 1992 are available at NORSAR on a continuous basis. The data are now processed jointly with data from the other regional arrays in northern Europe (NORESS and ARCESS in Norway, FINESA in Finland and GERESS in Germany) in the Intelligent Monitoring System (IMS). Over time, records from many Khibiny Massif mining explosions will accumulate in the IMS data base and will constitute excellent data for research, when taking into account the information on these explosions provided by the Kola Regional Seismological Centre.

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Mine	Location		Azimuth (deg)	Distance (km)
I, Underground	67.6702°N	33.7285°E	50.36	17.82
I, Open-pit	67.665°N	33.744°E	53.12	17.98
II	67.647°N	33.761°E	59.83	17.48
III	67.631°N	33.835°E	68.97	19.57
IV	67.624°N	33.896°E	73.30	21.79
V	67.632°N	34.011°E	74.38	26.73
VI	67.665°N	34.146°E	70.81	33.29

Table 1. The table gives the location of the six mines in the Khibiny Massif shown in Fig. 3. The azimuth and distance from the Apatity three-component station are also given for each mine.

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1991	06	15	12.14.19.3	epg	-	-	iii	8
1991	06	16	05.39.54.4	ipg	212.4	0.6	i	115
1991	06	16	06.35.16.9	ipg	19.8	0.7	i	15
1991	06	18	10.06.56.7	ipg	30.6	0.6	iv	118
1991	06	21	08.54.02.1	ipg	57.2	1.0	v	77
1991	06	23	04.14.04.4	ipg	162.0	0.7	i	80
1991	06	23	05.44.00.4	ipg	25.2	0.7	i	15
1991	06	25	09.48.16.1	ipg	28.0	1.0	iv	98
1991	06	28	11.16.00.6	ipg	78.0	1.0	iv	350
1991	06	30	06.33.05.0	ipg	270.0	0.7	i	120
1991	07	02	10.01.39.2	ipg	16.0	0.5	iv	75
1991	07	05	12.33.17.3	ipg	111.2	1.0	iv	380
1991	07	06	19.24.02.2	ipg	137.5	0.4	iii	94
1991	07	09	10.57.20.3	ipg	18.0	0.6	v	242
1991	07	12	10.21.22.4	ipg	63.8	0.9	v	392
1991	07	12	13.20.04.8	ipg	60.0	0.8	iv	300
1991	07	23	09.11.35.0	ipg	54.6	1.0	v	310
1991	07	23	10.32.24.7	ipg	34.0	0.8	iv	50
1991	07	26	08.27.48.7	ipg	27.0	0.6	v	275
1991	07	26	12.31.00.0	epg	100.0	0.8	iv	430
1991	07	28	05.43.12.8	ipg	21.5	0.5	i	10
1991	07	30	15.59.47.4	ipg	43.0	0.5	iv	105
1991	08	04	12.49.55.8	ipg	414.0	0.9	i	120
1991	08	06	12.31.53.7	ipg	49.5	0.5	iv	74
1991	08	09	07.20.58.2	epg	85.5	0.7	v	290
1991	08	10	18.00.05.2	ipg	70.3	0.7	iii	50
1991	08	13	15.25.56.7	ipg	30.0	0.4	iv	95
1991	08	16	08.09.58.4	ipg	25.8	0.5	v	235

Table 2. The table gives information on individual mining shots in the six Khibiny Massif mines during 15 June 1991 - 20 September 1992. The amplitude A is in nm, and the period T in seconds. The explosive yield is in tons. The information has been provided by the Kola Regional Seismological Centre. (Page 1 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1991	08	16	13.24.57.8	ipg	75.6	0.6	iv	335
1991	08	18	06.11.47.4	ipg	165.0	0.8	i	90
1991	08	20	09.57.03.1	ipg	27.0	0.6	iv	80
1991	08	23	08.24.19.6	ipg	92.0	0.9	v	263
1991	08	30	08.00.31.4	ipg	27.0	0.6	v	205
1991	09	03	10.18.57.9	ipg	45.0	0.4	iv	12
1991	09	05	05.09.29.9	ipg	84.6	0.6	v	262
1991	09	06	08.20.57.1	ipg	28.5	0.7	iv	39
1991	09	08	05.35.33.7	ipg	14.4	0.6	i	8
1991	09	13	09.03.50.1	ipg	45.0	0.6	v	235
1991	09	15	04.07.46.0	epg	145.8	0.7	i	57
1991	09	16	12.19.27.0	epg	16.0	0.8	ii	35
1991	09	19	16.45.10.9	ipg	32.5	0.7	iv	240
1991	09	21	11.39.57.8	epg	-	-	i	12
1991	09	22	05.36.35.4	ipg	36.5	0.5	i	12
1991	09	25	10.07.34.9	ipg	27.0	0.7	iv	220
1991	09	27	08.36.01.3	ipg	40.0	0.8	v	185
1991	09	29	06.37.30.7	ipg	18.0	0.6	i	10
1991	10	03	10.49.44.9	isg	63.0	0.7	v	10
1991	10	06	07.03.29.6	ipg	23.4	0.7	i	14
1991	10	11	06.50.44.1	ipg	33.0	0.9	v	142
1991	10	11	13.46.24.7	ipg	105.6	0.9	iv	190
1991	10	15	11.10.03.0	epg	16.2	0.6	iv	120
1991	10	17	10.04.51.6	esg	353.0	1.0	v	58
1991	10	18	09.01.29.4	ipg	23.4	0.7	v	83
1991	10	18	15.02.32.2	ipg	34.0	0.8	iv	474
1991	10	20	04.37.02.4	epg	116.0	0.8	i	100
1991	10	20	07.10.15.0	ipg	32.3	0.7	i	10
1991	10	25	10.06.59.1	epg	32.4	0.7	v	180
1991	10	26	13.03.16.6	ipg	79.2	0.9	iii	30
1991	10	27	01.32.34.9	ipg	60.0	0.5	i	12
1991	10	27	07.16.43.8	ipg	12.0	0.5	i	9

Table 2. (cont.) (Page 2 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1991	10	31	09.59.02.0	epg	-	-	v	20
1991	11	01	08.28.54.1	ipg	80.0	0.8	v	150
1991	11	01	14.47.43.9	ipg	54.0	0.7	iv	474
1991	11	03	07.52.22.5	ipg	18.0	0.6	i	15
1991	11	06	09.18.30.8	ipg	-	-	v	100
1991	11	12	13.26.51.1	epg	-	-	iv	120
1991	11	14	11.36.34.6	ipg	33.0	0.9	v	155
1991	11	15	12.45.29.4	ipg	36.0	0.8	v	146
1991	11	15	13.54.22.8	isg	22.0	0.9	iii	10
1991	11	16	12.35.36.8	ipg	62.5	0.4	iii	52
1991	11	17	04.59.22.6	ipg	212.0	0.8	i	150
1991	11	17	07.14.33.8	ipg	20.0	0.8	i	12
1991	11	22	09.04.38.8	ipg	32.0	0.8	v	163
1991	11	22	13.31.38.7	ipg	20.0	1.0	iii	15
1991	11	23	13.25.36.3	ipg	14.0	0.5	iii	12
1991	11	27	14.04.02.7	ipg	50.0	0.5	iii	320
1991	11	30	13.12.55.5	ipg	88.0	0.9	iii	70
1991	12	01	07.23.09.4	ipg	43.2	0.7	i	16
1991	12	06	09.53.06.4	ipg	55.0	0.9	v	172
1991	12	07	12.35.12.2	epg	-	-	iii	12
1991	12	08	08.29.33.5	ipg	144.0	0.6	i	167
1991	12	11	13.25.16.2	ipg	40.0	0.8	iii	289
1991	12	12	11.15.28.2	isg	46.8	1.0	v	18
1991	12	13	08.55.07.9	ipg	36.0	0.6	v	256
1991	12	13	13.37.06.5	ipg	33.0	0.9	iii	37
1991	12	13	13.39.45.5	ipg	48.0	0.8	iv	180
1991	12	15	05.55.44.3	ipg	180.0	0.7	ii	71
1991	12	15	09.21.19.7	ipg	56.0	0.8	i	12
1991	12	17	10.28.21.3	ipg	38.0	0.5	iv	100
1991	12	20	12.07.16.9	ipg	23.4	0.6	v	247
1991	12	20	14.17.50.2	ipg	44.0	0.8	iv	210
1991	12	22	07.25.37.9	ipg	304.0	0.9	i	239

Table 2. (cont.) (Page 3 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1991	12	25	10.56.47.7	epg	10.8	0.5	v	28
1991	12	27	09.18.09.1	ipg	67.6	1.0	v	235
1991	12	27	12.22.41.7	ipg	18.0	0.7	iv	270
1991	12	28	15.52.03.7	ipg	207.0	0.7	iii	380
1991	12	29	08.37.04.5	ipg	64.5	1.3	v	77
1991	12	31	08.48.51.4	ipg	205.0	0.7	i	205
1992	01	04	07.47.37.6	ipg	26.0	0.8	v	25
1992	01	10	08.23.03.0	ipg	43.2	0.6	v	114
1992	01	10	14.24.42.4	ipg	50.0	0.4	iv	250
1992	01	17	08.58.15.1	ipg	18.0	0.7	v	30
1992	01	17	11.42.40.5	ipg	41.4	0.7	iv	221
1992	01	17	13.27.09.6	esg	59.8	1.0	iii	17
1992	01	18	12.44.46.3	ipg	64.0	0.8	iii	40
1992	01	19	06.43.11.4	ipg	20.0	0.8	i	4
1992	01	24	08.08.05.9	ipg	64.0	0.8	v	151
1992	01	24	12.35.49.3	epg	19.8	0.6	iv	151
1992	01	26	06.46.03.0	ipg	54.0	0.7	i	7
1992	01	31	08.29.02.4	ipg	34.0	0.8	v	140
1992	01	31	12.43.14.2	ipg	75.4	1.0	iv	435
1992	02	02	05.05.03.2	ipg	433.0	0.9	i	110
1992	02	04	09.30.06.8	epg	-	-	v	15
1992	02	07	08.41.09.0	ipg	98.9	1.3	v	280
1992	02	08	11.29.48.7	ipg	21.6	0.6	iii	10
1992	02	09	04.09.44.1	ipg	864.0	0.8	i	120
1992	02	14	08.48.21.9	ipg	65.0	1.0	v	290
1992	02	14	11.50.37.7	ipg	63.8	0.9	iv	66
1992	02	16	08.49.53.0	ipg	168.0	0.8	i	168
1992	02	19	12.44.02.7	ipg	108.0	0.6	iv	360
1992	02	20	09.19.03.9	ipg	16.2	0.6	v	50
1992	02	21	08.59.28.3	ipg	57.2	1.0	v	320
1992	02	22	12.00.21.9	ipg	95.4	0.7	iii	74
1992	02	23	05.37.05.3	ipg	341.0	0.9	i	106

Table 2. (cont.) (Page 4 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1992	02	25	12.46.55.1	ipg	34.0	0.8	iv	94
1992	02	28	08.59.02.8	ipg	66.5	0.7	v	295
1992	02	28	14.41.28.3	ipg	17.2	0.5	iii	12
1992	03	01	07.25.00.6	ipg	38.7	0.5	i	14
1992	03	13	15.31.20.4	ipg	57.6	0.6	v	273
1992	03	15	07.03.10.7	ipg	-	-	i	7
1992	03	20	08.31.50.6	ipg	63.0	0.7	v	235
1992	03	27	09.20.13.5	ipg	78.0	1.0	v	250
1992	03	31	07.54.20.6	ipg	78.0	1.0	v	90
1992	04	03	06.27.25.5	ipg	99.0	0.7	v	160
1992	04	03	11.51.57.1	ipg	66.0	1.1	iv	90
1992	04	05	05.19.01.6	isg	18.0	0.8	i	10
1992	04	07	14.39.27.4	ipg	30.0	0.4	iv	57
1992	04	10	09.10.33.7	ipg	91.8	0.7	v	199
1992	04	10	09.22.06.3	ipg	45.0	0.7	iv	320
1992	04	12	05.19.48.7	ipg	27.0	0.7	i	12
1992	04	17	10.04.40.6	ipg	78.0	1.0	iv	413
1992	04	19	02.33.24.6	ipg	236.0	0.8	i	60
1992	04	19	05.10.41.5	epg	14.4	0.7	i	10
1992	04	21	14.21.22.1	ipg	19.8	0.7	iv	30
1992	04	24	11.33.43.2	ipg	32.4	0.7	iv	310
1992	04	25	13.39.04.0	ipg	364.8	0.9	iii	150
1992	04	26	03.31.59.7	ipg	234.0	0.7	i	92
1992	04	26	05.19.34.2	ipg	15.0	0.4	i	6
1992	04	28	14.30.00.7	epg	50.0	0.8	iv	520
1992	04	30	06.35.28.9	ipg	52.0	1.0	vi	144
1992	05	01	02.14.14.6	ipg	50.0	0.8	iii	60
1992	05	01	03.03.00.8	ipg	602.6	1.0	i	150
1992	05	05	10.02.57.8	ipg	36.0	0.8	iv	100
1992	05	08	11.27.03.0	esg	14.0	0.5	iii	10
1992	05	08	11.31.07.8	ipg	21.6	0.6	iv	347
1992	05	15	07.35.53.2	ipg	39.0	1.0	vi	200

Table 2. (cont.) (Page 5 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1992	05	15	11.46.13.5	ipg	30.0	0.5	iv	524
1992	05	22	09.26.55.2	ipg	168.0	0.8	v	302
1992	05	24	04.30.00.2	epg	45.0	0.7	i	125
1992	05	24	04.30.06.2	esg	210.0	0.5	ii	130
1992	05	24	04.30.20.2	epg	-	-	i	5.5
1992	05	29	07.24.32.4	ipg	83.6	0.9	vi	353
1992	05	29	11.48.18.7	ipg	28.5	0.7	iv	310
1992	05	31	02.46.45.0	ipg	14.4	0.6	i	26
1992	05	31	03.41.13.0	ipg	208.0	1.0	i	217
1992	06	05	07.40.57.8	ipg	25.0	0.4	v	246
1992	06	05	11.43.03.0	ipg	62.7	0.7	iv	315
1992	06	05	10.29.08.0	isg	82.8	1.2	iii	16
1992	06	07	03.47.39.8	ipg	200.0	0.8	i	108
1992	06	10	14.33.09.8	ipg	46.2	0.3	iv	300
1992	06	11	07.11.55.8	ipg	15.2	0.7	v	280
1992	06	16	14.05.38.6	ipg	30.0	0.4	iv	40
1992	06	19	08.22.13.6	ipg	32.2	0.5	v	235
1992	06	19	11.23.38.4	ipg	11.6	0.6	iii	80
1992	06	21	04.02.15.0	ipg	25.0	0.4	i	3.5
1992	06	24	15.16.16.5	ipg	22.8	0.7	vi	49
1992	06	26	08.31.37.1	ipg	14.0	0.8	v	65
1992	06	28	05.23.44.0	ipg	30.0	0.4	i	7
1992	06	30	15.15.05.4	ipg	80.0	0.8	v	120
1992	07	03	10.08.00.5	ipg	25.8	0.5	v	63
1992	07	05	04.01.43.5	ipg	200.0	0.8	i	110
1992	07	07	14.20.32.2	epg	9.0	0.6	v	89
1992	07	10	10.18.27.0	ipg	48.0	0.8	iv	350
1992	07	12	03.24.49.3	ipg	114.0	0.7	i	117
1992	07	12	04.10.32.3	ipg	32.2	0.5	i	8
1992	07	19	04.25.06.2	ipg	17.5	0.4	i	6
1992	07	26	03.56.09.4	ipg	138.0	0.8	i	40
1992	07	31	09.57.39.9	ipg	39.0	1.0	iv	460

Table 2. (cont.) (Page 6 of 7)

YY	MM	DD	HR	Phase	A	T	Mine	Yield
1992	08	05	15.07.33.6	epg	-	-	iv	72
1992	08	05	15.08.29.5	ipg	78.0	1.0	iv	140
1992	08	07	14.08.11.7	ipg	27.0	0.7	iv	80
1992	08	22	10.43.57.0	epg	-	-	iii	15
1992	08	23	03.10.46.4	ipg	280	0.8	i	65
1992	08	28	06.34.39.4	ipg	33.0	0.9	v	160
1992	08	28	11.39.57.0	ipg	-	-	iv	290
1992	08	29	09.28.22.3	isg	48.4	0.9	iii	15
1992	08	30	03.11.59.4	ipg	524	1.0	i	150
1992	09	04	07.59.12.1	ipg	36	0.8	v	194
1992	09	18	07.23.09.7	ipg	80.0	0.8	v	203
1992	09	20	05.09.32.8	ipg	23.4	0.6	i	8

Table 2. (cont.) (Page 7 of 7)

Event id	YY	MM	DD	Arrival time	Navail	Mine	Yield
Apa2	91	06	16	05.39.54.4	3	I(u)	115
Apa3	91	06	16	05.35.17.0	3	I(o)	15
Apa4	91	06	18	10.06.56.6	3	IV	118
Apa6	91	06	23	04.14.03.7	3	I(u)	80
Apa7	91	06	23	05.44.00.0	3	I(o)	15
Apa8	91	06	25	09.48.15.9	2	IV	98
Apa9	91	06	28	11.16.00.6	2	IV	350
Apa11	91	07	02	10.01.39.2	2	IV	75
Apa12	91	07	05	12.33.17.2	3	IV	380
Apa13	91	07	06	19.24.02.1	3	III	94
Apa14	91	07	09	10.57.20.5	3	V	242
Apa15	91	07	12	10.21.22.1	3	V	392
Apa16	91	07	12	13.20.04.6	3	IV	300
Apa18	91	07	23	10.32.24.8	3	IV	50
Apa19	91	07	26	08.27.48.7	3	V	275
Apa20	91	07	26	12.31.00.3	3	IV	430
Apa22	91	07	30	15.59.47.0	1	IV	105
Apa23	91	08	04	12.49.53.8	3	I(u)	120
Apa25	91	08	09	07.20.58.1	1	V	290
Apa26	91	08	10	18.00.05.1	1	III	50
Apa27	91	08	13	15.25.56.4	3	IV	95
Apa28	91	08	16	08.09.57.5	3	V	235
Apa29	91	08	16	13.24.57.2	3	IV	335
Apa39	91	09	15	04.07.46.1	3	I(u)	57
Apa40	91	09	16	12.19.27.2	3	II	35
Apa46	91	09	29	06.37.30.6	3	I(o)	10

Table 3. The table gives the Khibiny Massif mining shots analyzed in this study. The arrival time is the P arrival time as read from the digital records. "Navail" gives the number of components for which data are available (see text for explanation). For Mine I, (u) denotes underground explosion and (o) open-pit explosion. (Page 1 of 3)

Event id	YY	MM	DD	Arrival time	Navail	Mine	Yield
Apa48	91	10	06	07.03.29.9	3	I(o)	14
Apa53	91	10	18	09.01.28.4	3	V	83
Apa54	91	10	18	15.02.31.1	3	IV	474
Apa55	91	10	20	04.37.09.2	3	I(u)	100
Apa56	91	10	20	07.10.14.6	3	I(o)	10
Apa58	91	10	26	13.03.16.3	3	III	30
Apa59	91	10	27	01.32.35.0	3	I(o)	12
Apa60	91	10	27	07.16.44.0	3	I(o)	9
Apa62	91	11	01	08.28.54.0	3	V	150
Apa63	91	11	01	14.47.43.7	3	IV	474
Apa64	91	11	03	07.52.22.6	3	I(o)	15
Apa172	92	06	16	14.05.39.1	3	IV	40
Apa173	92	06	19	08.22.13.4	3	V	235
Apa174	92	06	19	11.23.39.1	3	III	80
Apa175	92	06	21	04.02.15.1	3	I(o)	3.5
Apa176	92	06	24	15.16.16.5	3	VI	49
Apa177	92	06	26	08.31.37.1	3	V	65
Apa178	92	06	28	05.23.44.5	3	I(o)	7
Apa179	92	06	30	15.15.05.6	3	V	120
Apa181	92	07	05	04.01.43.9	3	I(u)	110
Apa182	92	07	07	14.20.33.7	3	V	89
Apa183	92	07	10	10.18.28.1	3	IV	350
Apa184	92	07	12	03.24.51.1	3	I(u)	117
Apa185	92	07	12	04.10.33.9	3	I(o)	8
Apa186	92	07	19	04.25.07.5	3	I(o)	6
Apa187	92	07	26	03.56.10.9	3	I(u)	40
Apa189	92	08	05	15.07.33.9	3	IV	72
Apa190	92	08	05	15.08.29.9	3	IV	140
Apa191	92	08	07	14.08.13.1	3	IV	80
Apa192	92	08	22	10.43.59.8	3	III	15

Table 3. (cont.) (Page 2 of 3)

Event id	YY	MM	DD	Arrival time	Navail	Mine	Yield
Apa193	92	08	23	03.12.00.8	3	I(u)	65
Apa196	92	08	29	09.28.21.5	3	III	15
Apa197	92	08	30	03.11.59.4	3	I(u)	150
Apa199	92	09	18	07.23.11.0	3	V	203
Apa200	92	09	20	05.09.34.3	3	I(o)	8

Table 3. (cont.) (Page 3 of 3)

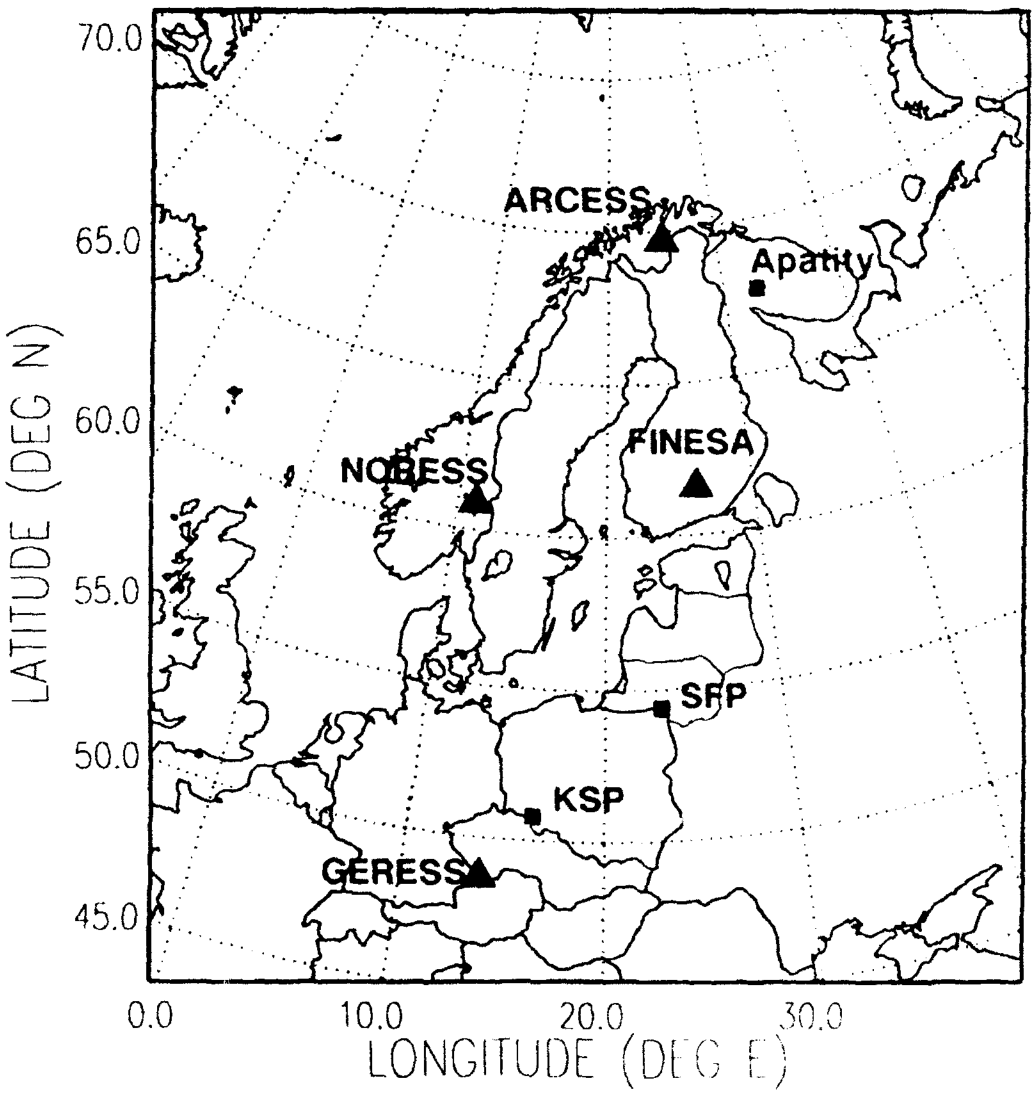

Fig. 1. The figure shows the arrays (triangles) and three-component stations (squares) that contributed data to the NORSAR Data Processing Center during June 1991 - September 1992.

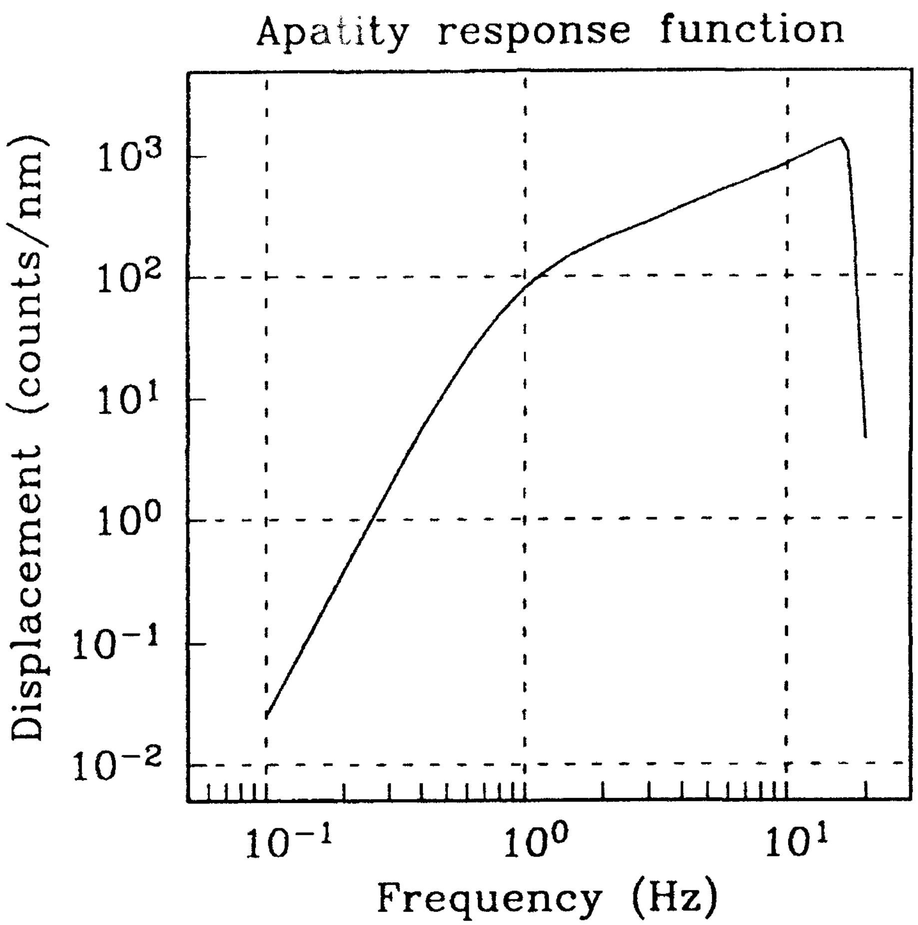

Fig. 2. Amplitude (displacement) response function for the three-component station installed in Apatity in June 1991.

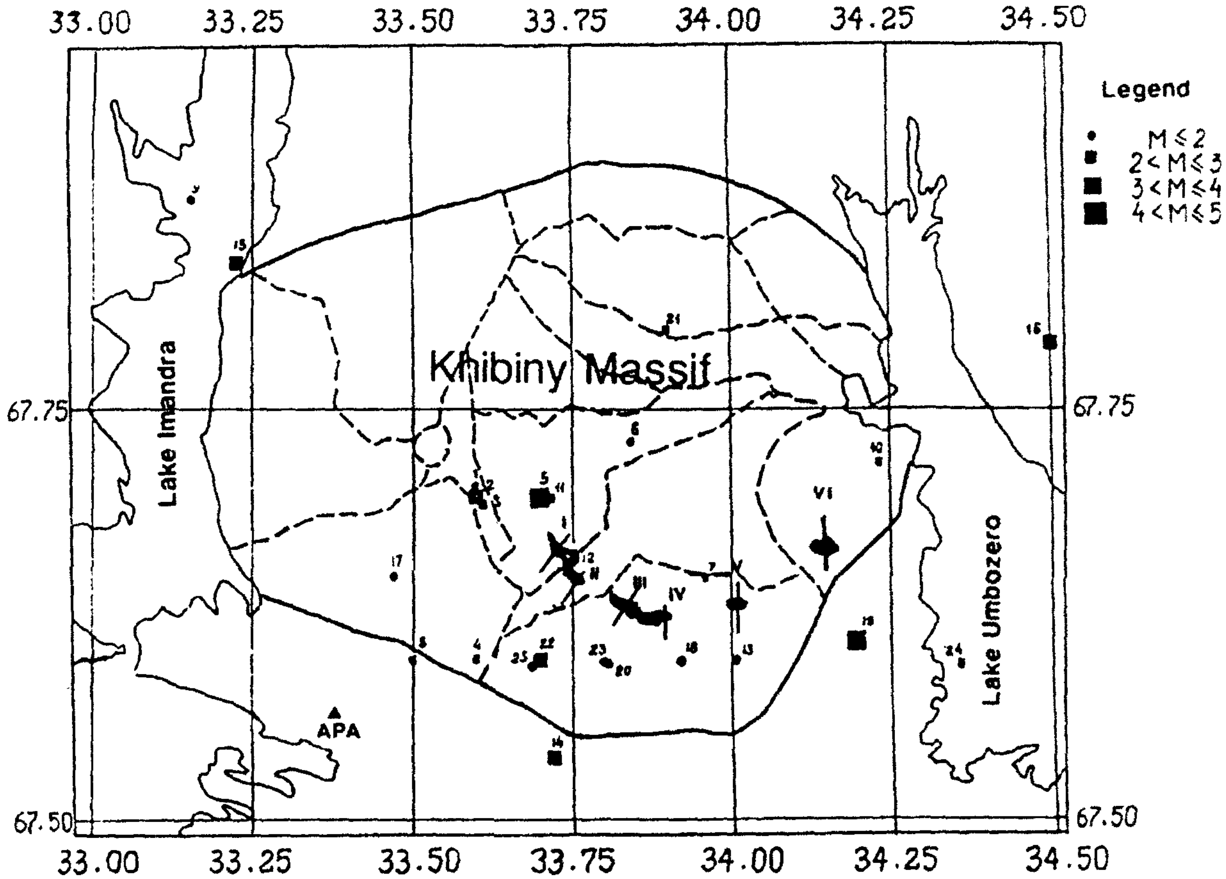

Fig. 3. Map of the Apatity area, showing the location of the Apatity three-component station (APA). Also shown is the mining area of the Khibiny Massif, and the division into six (denoted I-VI) separate subareas where explosions are currently taking place. Locations for 25 mining-induced earthquakes (magnitude range 2-5) are also shown (see Kremenetskaya, 1991).

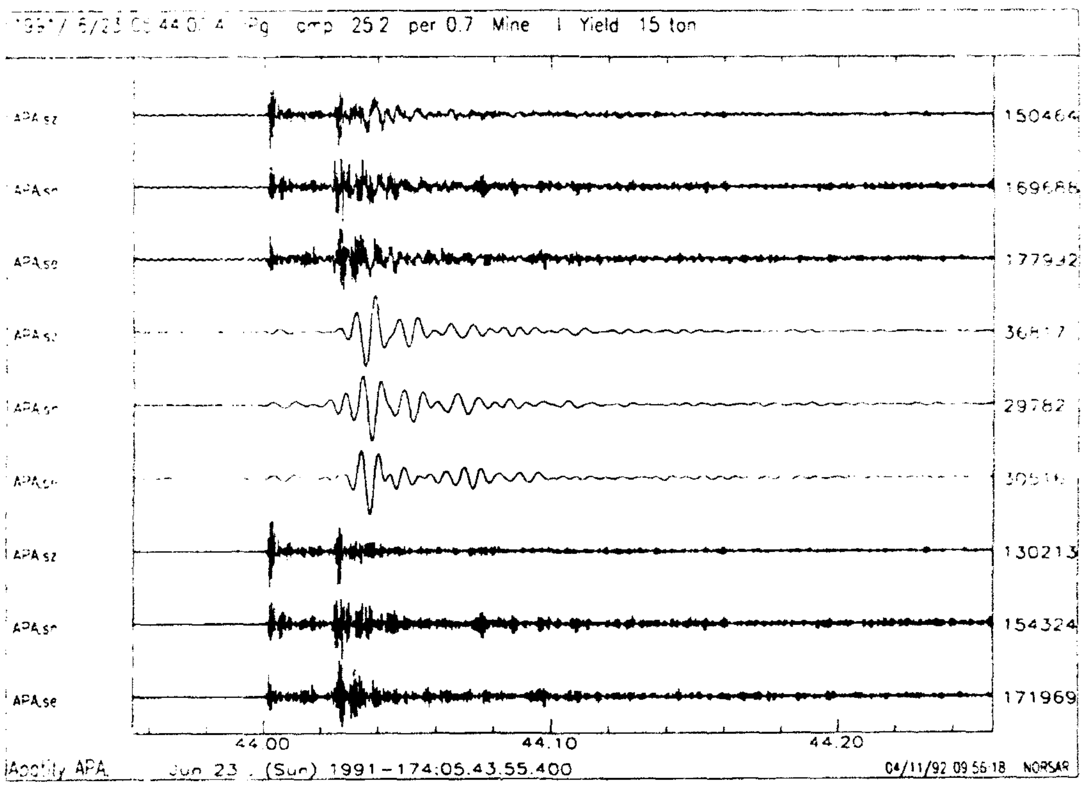

Fig. 4. Apatity three-component station data for the event denoted "Apa7" in Table 3. The upper three traces are unfiltered data, the next three are the data filtered in the 0.5-2.0 Hz band, and the bottom three traces show the data filtered in the 7-16 Hz band.

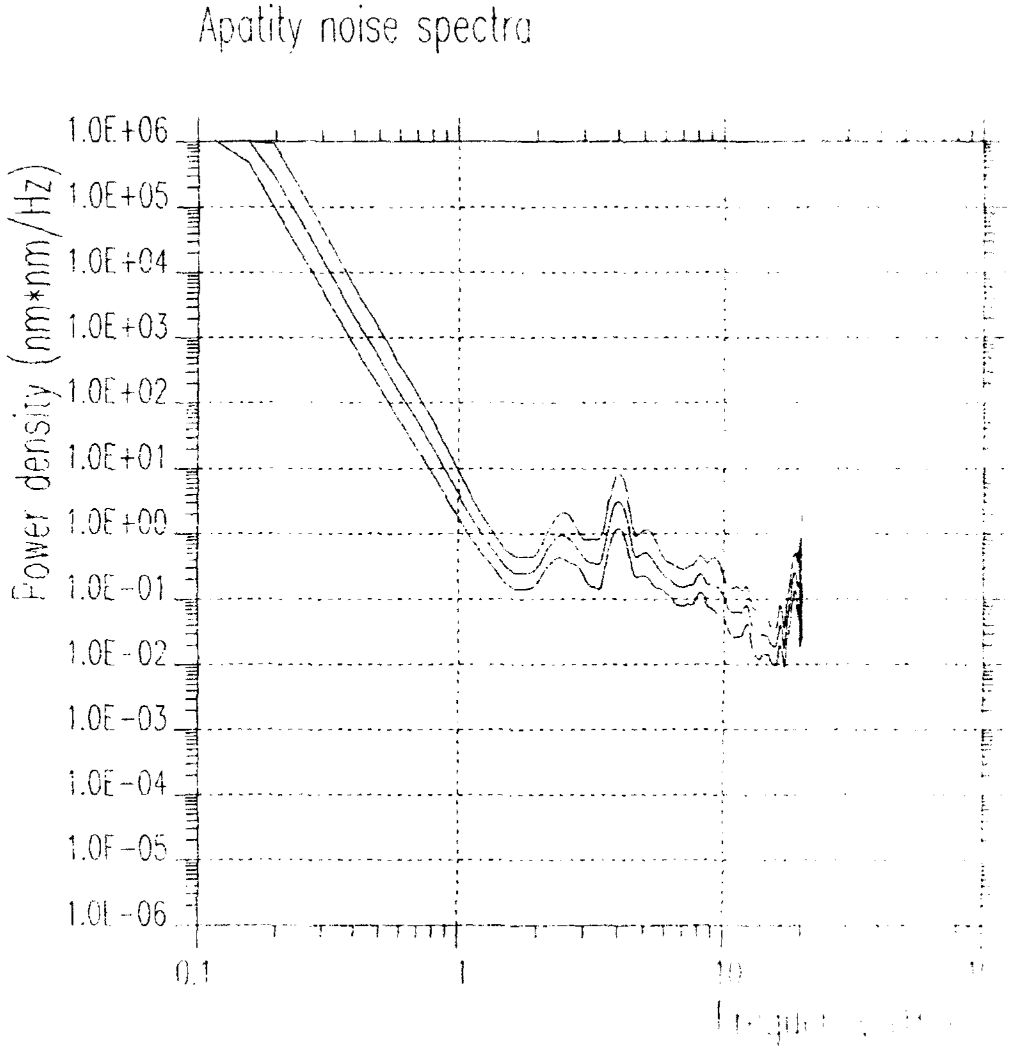

Fig. 5. The middle curve gives the average Apatity three-component station noise level, and the upper and lower curves represent plus/minus one standard deviation. respectively. 61 noise samples, each 30 seconds long, were used to compute the average noise level in this figure.

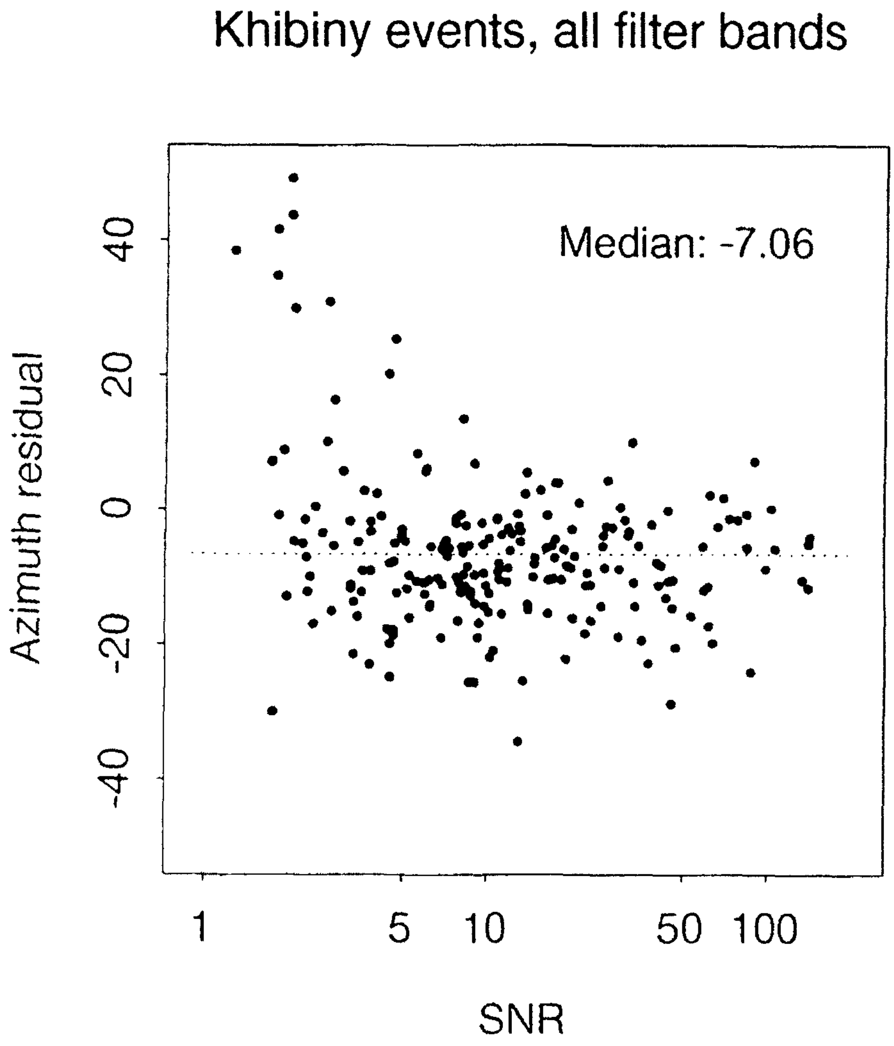

Fig. 6. Azimuth residuals (estimated azimuth minus true azimuth) as resulting from broad band slowness analysis of P-waves from Khibiny mining explosions recorded at the Apatity three-component station.

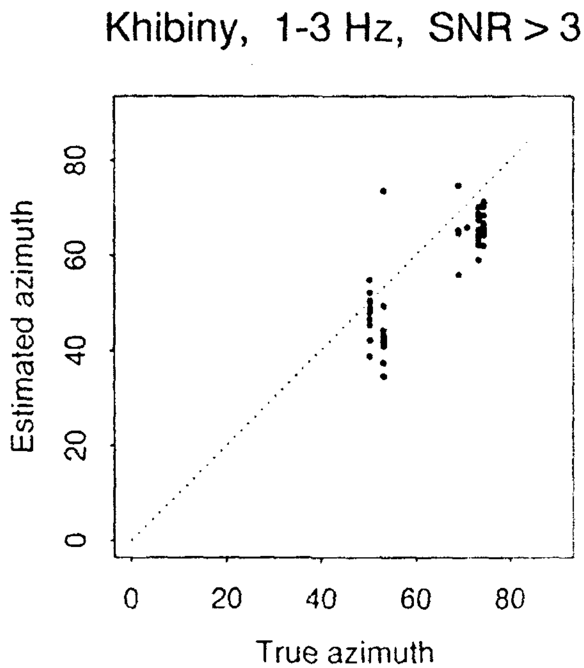

Fig. 7. True versus estimated azimuth for P-waves from Khibiny mining explosions recorded at the Apatity three-component station, for the frequency band 1-3 Hz. Only P-wave arrivals with an SNR exceeding 3 are included.

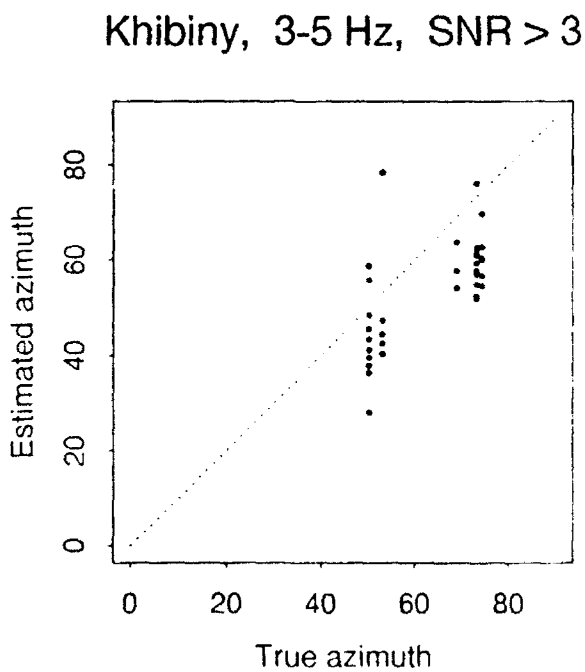

Fig. 8. Same as Fig. 7, but for the frequency band 3-5 Hz.

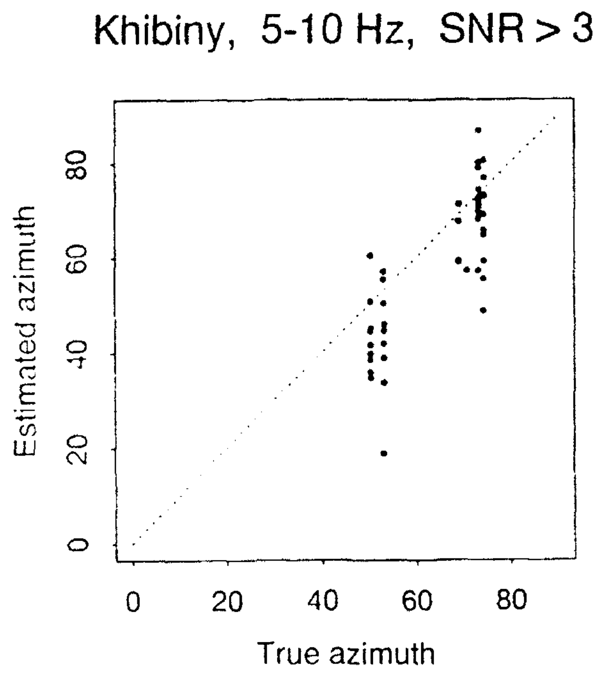

Fig. 9. Same as Fig. 7, but for the frequency band 5-10 Hz.

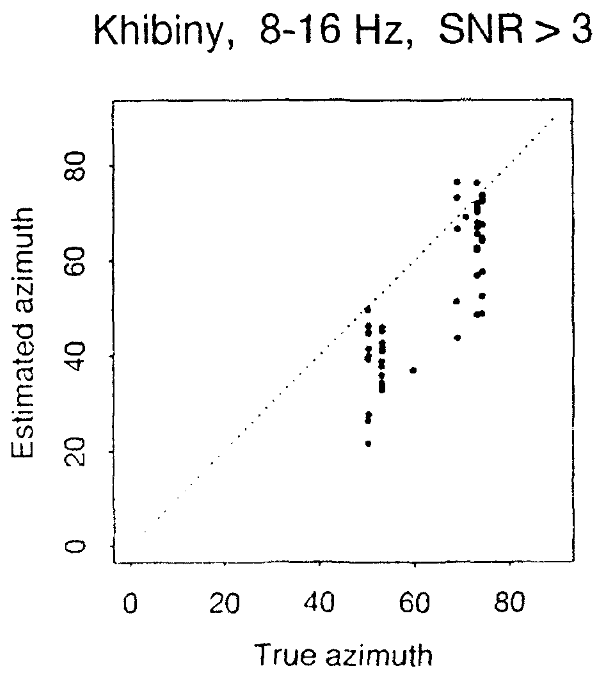

Fig. 10. Same as Fig. 7, but for the frequency band 8-16 Hz.

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